

# Modeling of Direct Beam Extraction for a High- Charge-State Fusion Driver

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This article was submitted to  
7<sup>th</sup> International Conference on Ion Sources  
Taormina, Italy  
September 7-13, 1997

**March 19, 2001**

**U.S. Department of Energy**

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This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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# Modeling of Direct Beam Extraction for a High-Charge-State Fusion Driver

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## Abstract

A newly proposed type of multicharged ion source offers the possibility of a economically advantageous high-charge-state fusion driver. Multiphoton absorption in an intense uniform laser focus can give multiple charge states of high purity, simplifying or eliminating the need for charge-state separation downstream. Very large currents (hundreds of amperes) can be extracted from this type of source. Several arrangements are possible. For example, the laser plasma could be tailored for storage in a magnetic bucket, with beam extracted from the bucket. A different approach, described in this report, is direct beam extraction from the expanding laser plasma. We discuss extraction and focusing for the particular case of a 4.1-MV beam of  $\text{Xe}^{16+}$  ions. The maximum duration of the beam pulse is limited by the total charge in the plasma, while the practical pulse length is determined by the range of plasma radii over which good beam optics can be achieved. The extraction electrode contains a solenoid for beam focusing. Our design studies were carried out first with an envelope code and then with a self-consistent particle code. Results from our initial model showed that hundreds of amperes could be extracted, but that most of this current missed the solenoid entrance or was intercepted by the wall and that only a few amperes were able to pass through. We conclude with an improved design which increases the surviving beam to more than 70 amperes.

## I. INTRODUCTION

The idea of using multicharged ions for heavy ion fusion is an old one, and the challenges associated with the final focus and front end have been discussed before. Another paper at this conference [1] describes new work on the final focus, while here we are concerned with the front end, and in particular with direct beam extraction from a laser ion source. (We consider the alternative of extraction from a magnetic bucket in a future paper.) Before discussing direct beam extraction, we take a brief overall look at the multicharge approach.

### A. Background

Conventional HIF induction-accelerator designs using singly charged ions are rather long—one or two kilometers. Higher charge-state ions (e.g.,  $q = 8$  to 16) reduce the length by a factor of  $q$  while the total beam current is increased by the same factor. These effects can reduce the dominant magnetic core and pulser costs. Indeed, in 1988 the HIFSA study [2] found significant cost savings using heavy ions of charge state  $q=3$ , but further pursuit of high- $q$  designs was discouraged because of (a) the tendency of higher space charge to increase the size of the final focus; (b) beam transport costs in the low energy part of the accelerator, which the HIFSA study had neglected; and (c) poor charge-state purity in existing high- $q$  ion sources.

These three problems can be dealt with in the following way:

(a) Since the HIFSA study, PIC calculations [1] have shown that a cold-electron source at the beam entrance to the target chamber, such as might be provided by a dense plasma focusing lens, may neutralize high- $q$  ions sufficiently for ballistic transport to the target, while avoiding beam-beam deflections as well.

(b) Using a solenoid field in the extractor electrode can provide magnetic insulation and allow acceleration of hundreds of amperes with diode voltages of several megavolts. This simplifies the front end by eliminating the need for ESQ focusing arrays and beam merging.

(c) The advent of intense, ultra-short-pulse lasers now suggests that specific high- $q$  charge states can be produced by multiphoton absorption with minimal collisional ionization [3].

The direct extraction laser-ion source concept is shown schematically in Fig. 1. A pellet of noble gas such as xenon is injected into a diode gap near the small anode while the voltage is initially off. A low energy laser prepulse shocks the 5 to 10 micron-radius pellet into a gas

which expands until the density is so low that recombination will not occur after the gas is ionized. A second, intense, laser pulse ( $\sim 100$  femtoseconds) strips the ions down to a common ionization level by multiphoton absorption that is controlled by the laser intensity (typically  $10^{16}$  W/cm<sup>2</sup>). The diode voltage is applied about 20 ns later. As the laser plasma expands, ions are extracted from the plasma sheath until the ion density is depleted; the extraction period in most designs is between 1 and 10  $\mu$ sec. The field of a solenoid within the extraction electrode focuses the beam. Figure 1 shows an outer reversed solenoid for reducing the stray field; there is also a bucking coil near the anode to produce a field null at the laser pellet.

### *B. Beam Extraction and Focusing*

Because of the large currents required, beam extraction imposes difficulties for most HIF schemes. Direct extraction from a laser plasma is especially demanding because it requires a current of hundreds of amperes to be extracted from a small spherical plasma as its diameter expands over a large range such as 0.1 to 10 cm. Spherical diode theory predicts that such large radial currents can be obtained with feasible extraction voltages (Section II). It is not obvious, however, that a sufficient fraction of this current can be deflected, focused, and matched into the transport and acceleration system downstream or that sufficiently good beam quality can be achieved.

The problem can be visualized in terms of the reverse problem: starting with the eventually parallel transported beam and working backward, one is required to focus the beam onto a small spot on the laser plasma with a very large convergence angle. For example, the required half-angle is  $45.6^\circ$  to represent extraction from 15% of the pellet area. I.e., the convergence half angle in the reverse problem is 0.80 radians. This is almost an order of magnitude larger than the angles typically needed for injection into high-current RFQs, and those angles are considered hard to produce without gas neutralization.

Our beam extraction studies were done in three stages, first using a spherical diode model to relate the extraction voltage to the current and radius (Section IIA) and then a special envelope code to investigate the feasibility of solenoid focusing (Section IIB). This code showed that the initial focusing solenoids would need to be much larger in diameter than originally proposed. The third stage of modeling used the TriComp self-consistent space charge code, which

confirmed the envelope code prediction (Section IIIA) and which was then used to test ideas for improved solenoid geometry (Section IIIB). The results are summarized in Section IV.

## II. PRELIMINARY MODELING OF BEAM EXTRACTION

### A. Spherical Diode Model

The theory for spherical diodes was developed in 1924 by Langmuir and Blodgett [4], who derived a governing differential equation and found a series expansion useful over a limited range of the ratio  $d/r$ , where  $d$  is the distance from the emitter and  $r$  is the spherical emitter radius. They expressed their result in terms of a slowly varying function  $\alpha(d/r)$  which equals  $d/r$  in the limit  $d/r \rightarrow 0$ . Recently, Humphries [5], taking advantage of modern computers, obtained numerical solutions for  $\alpha$  and published a table of values of  $d/r$  over the range 0 to 100000. In terms of  $\alpha$ , the current is (see Eq. 6.31 in Ref. [5])

$$I_{L-B} = FC (q/A)^{1/2} V_0^{3/2} \frac{1}{\alpha(d/r)^2}, \quad (1)$$

where  $F$  is the fraction of the sphere from which beam is extracted and  $C = 6.845 \times 10^{-7}$  in SI units. Eq. (1) can be expressed in terms of  $V_0$  as a function of  $d/r$ , as plotted in Fig. 2 for the case  $F = 0.25$ .

An approximate formula for the spherical diode is useful for present purposes rather than a table of values. We find that

$$I_{OA} = FC (q/A)^{1/2} V_0^{3/2} \left( 0.594 + \left( \frac{r}{d} \right)^{4/5} \right)^{5/2} \quad (2)$$

is accurate within 6% for  $0 < d/r < 100$ . Equation (2), also plotted in Fig. 2 with  $F = 0.25$ , was utilized in the envelope code discussed below.

One may compare an empirical formula given by Humphries [5] for emission from a cylindrical rod squared off at the end. In that case emission is enhanced at the sharp corners [5]. With  $r$  redefined as the radius of the cylinder,

$$I_{SH} = 0.25 C (q/A)^{1/2} V_0^{3/2} \left( \frac{1}{4} + \left( \frac{r}{d} \right)^2 \right). \quad (3)$$

This is also plotted in Fig. 2.

Equation (3) was used to estimate the parameters for direct extraction from a laser plasma in Ref. [7], but in the present study we use (1) or (2). Taking the example of  $V_0 = 4.1$  MV and

$d/r = 32$ , Eq. (1) predicts 107 A of  $\text{Xe}^{16+}$  ions if beam is extracted from 15% of the spherical surface.

### *B. Envelope Code Results*

Although an envelope code has limited accuracy for this type of problem, it provides a quick way to estimate the ability of the solenoid field to focus the beam. We used a model in which the electric potential varies on axis according to Eq. (2)—see Fig. 2—between the emitting surface and the entrance to the hollow cathode and was constant thereafter. The magnetic field was computed from the standard solenoid formula (see J. D. Jackson's text, for example). We chose a particular example for study:  $\text{Xe}^{16+}$  ions, emitting sphere radius 5 cm, extraction gap distance 160 cm, voltage 4.1 MV, current 144 A extracted over a  $54^\circ$  (half angle) segment of the sphere. The magnetic field was generated by a 90-cm-radius solenoid 160 cm from the emitter with asymptotic field 0.45 Tesla. (These numbers were taken from an example in Ref. [7].) There was a bucking solenoid on the other side which produced a null field at the emitter.

Using the above model, the envelope code showed that less than 52 A of beam current would enter an aperture of 90 cm radius at  $z = 160$  cm. Most of this current was diverging and the beam did not straighten out until  $z = 630$  cm, leaving a core of less than 7 A within the 90 cm limit. With the solenoid field doubled, to 0.9 Tesla, the beam straightened out at 360 cm, with 17 A surviving. A large B field increase is unrealistic because parts of the beam will be reflected by the mirror effect. It was clear that the design needed to be modified, and that a self consistent particle code was needed.

## III. SELF-CONSISTENT FIELD CALCULATIONS

### *A. Simulation of Original Concept*

In the direct extraction approach considered here, the emitter radius may initially be as small as a few millimeters while the hollow cathode radius may be one meter or more. This large scale range clearly requires a particle code with adjustable mesh. The TriComp code [8] features an adjustable triangular lattice and is easy to use. The author of the code offered to set up an initial simulation and was given the model described in Section IIB.

The results were similar to the above, except for a smaller total current, mainly because the outer electrode is not spherical (it is a cylinder off to one side) so that less current is emitted. Again, only a small fraction of the emitted current entered the solenoid and most of this was intercepted by the 90-cm-radius wall before the B field could straighten the diverging beam. The next step was to improve the extraction configuration.

### *B. Conical Solenoid Results*

Three improvements were required: (1) the magnetic field needed to ramp up faster to provide quicker deflection in the downstream direction; (2) the electrode needed to better approximate a spherical geometry to extract more current; (3) there needed to be more radial clearance, especially further downstream where the beam continues to expand before becoming parallel. The solenoid geometry that satisfies all these requirements is shown in Figs. 3. An obvious new feature seen here is that the hollow cathode that contains the solenoid winding is cone shaped to reduce beam scraping downstream. Like an ordinary solenoid, the conical solenoid gives a uniform magnetic field in its interior.

Because the solenoid/hollow cathode entrance is now at  $z = 40$  cm instead of 160 cm, the magnetic field ramps up quickly, as shown in Fig. 4. This configuration also causes the electric potential lines to curve around somewhat spherically on the front half of the emitter, as seen in Fig. 5. The entrance radius is increased as shown from 90 cm to 180 cm to provide more beam clearance. The breakdown gap (about 160 cm) to the nearest high voltage electrode remains the same as in the original design.

Figure 6 shows the beam trajectories in the new design. The effect of all the above changes is to increase the transmitted beam from a few amperes to 71 amperes. However, the outermost beamlet obviously suffers some aberration and further work is needed to improve the emittance.

## IV. SUMMARY AND DISCUSSION

We have shown that it is possible to extract, focus and transport a current of the order of one hundred amperes of  $\text{Xe}^{16+}$  ions directly from an expanding laser ion plasma. However, because the initial beam is strongly divergent, the beam expands to more than 3 meters radius



before converging; this is about five times larger than hoped for in the original concept. A bulky solenoid matching section would be required to channel the beam into the desired acceleration module of perhaps 80 cm radius.

Because of these difficulties with the direct extraction approach, we conclude that the above mentioned alternative of extracting the beam from a magnetic bucket may prove to be more feasible. The bucket would be loaded from a laser plasma configured to minimize the radial expansion energy. This alternative concept will be discussed in a subsequent paper.

## V. ACKNOWLEDGMENTS

We would like to thank Stan Humphries for his help in setting up the first TriComp model. This work was supported by U. S. Department of Energy under Contract W-7405-Eng-48.

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## FIGURE CAPTIONS

Fig. 1a. High charge state ion injector concept using ultra short pulse lasers.

Fig. 1b. Laser-ion plasma (detail).

Fig. 2. Normalized potential vs distance. Curve L-B represents the exact spherical diode solution (Eq. 1) with  $F = 0.25$ . Curve OA shows the approximation of Eq. (2) for  $F = 0.25$ . The rod model of Eq. (3) gives curve SH.

Fig. 3. Magnetic flux contours in improved model for direct extraction from laser plasma. The conical solenoid design allows room for beam to expand without striking the electrode.

Fig. 4. Magnetic field strength along z-axis for model of Fig. 3. The field on axis rises rapidly from 0 at the origin (plasma surface) to 0.2 Tesla at 0.32 meters. The maximum value, at 4.8 meters, is 0.364 Tesla.

Fig. 5. Electric potential contours for the model of Fig. 3. The potential is zero at the hollow cathode, which contains the first focusing coil, and reaches 4.1 MV at the plasma surface, the anode, and the bucking coil assembly.

Fig. 6. Beam traces in improved model for direct extraction from laser plasma (Figs. 3 and 5). The current which is captured without striking the hollow cathode is 71 amperes of  $\text{Xe}^{+16}$ .

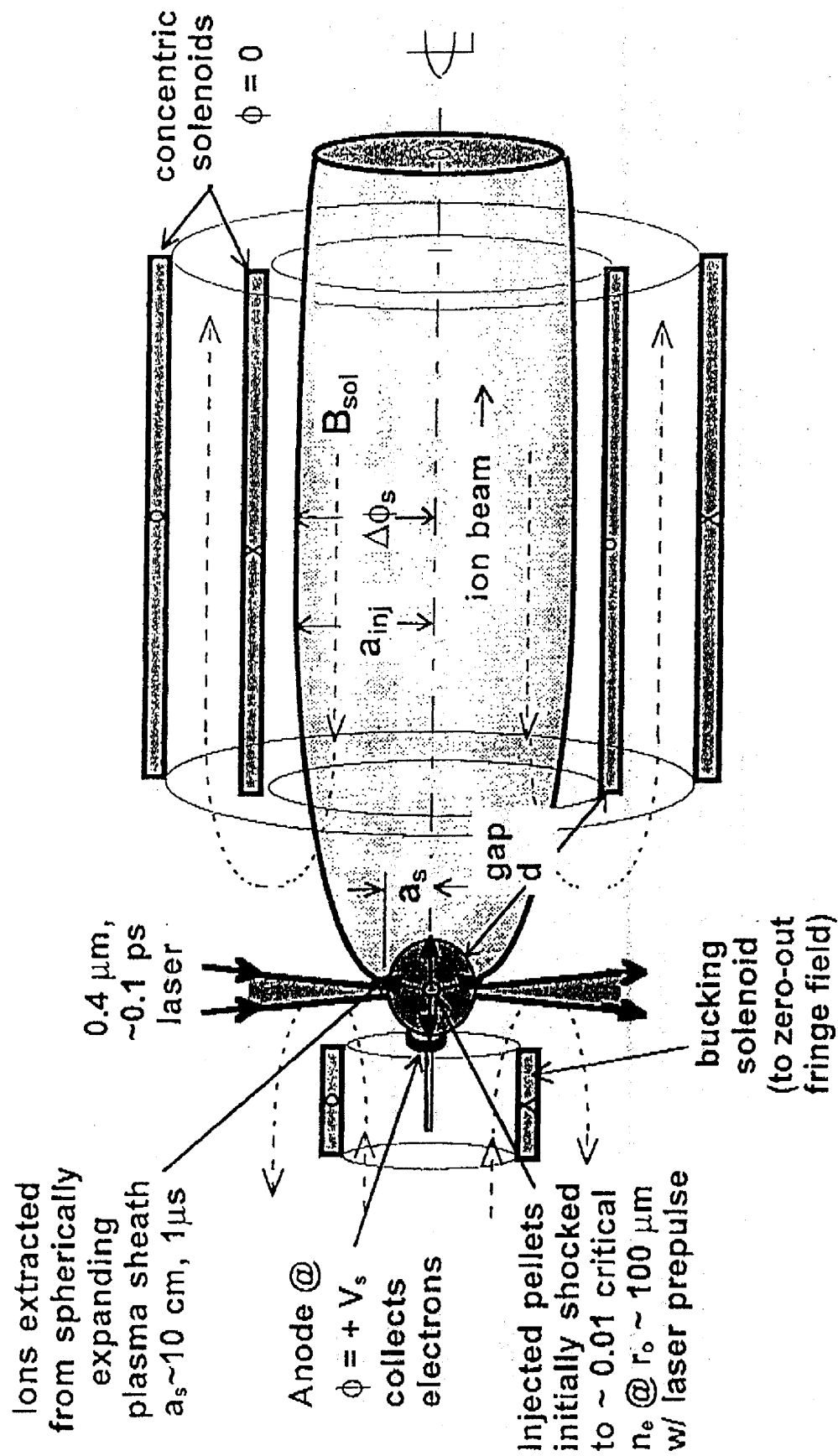


Fig. 1a

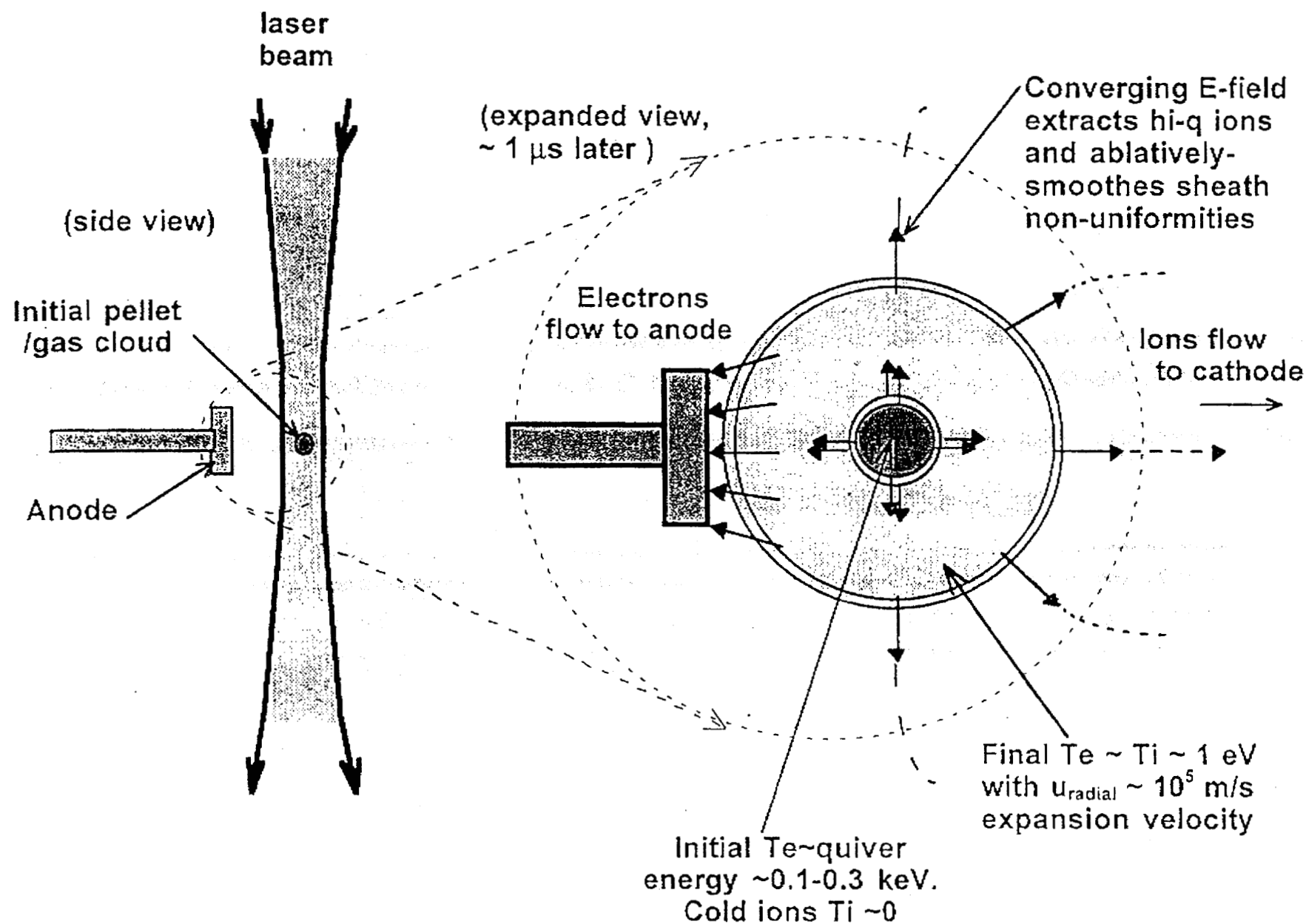


Fig. 1b

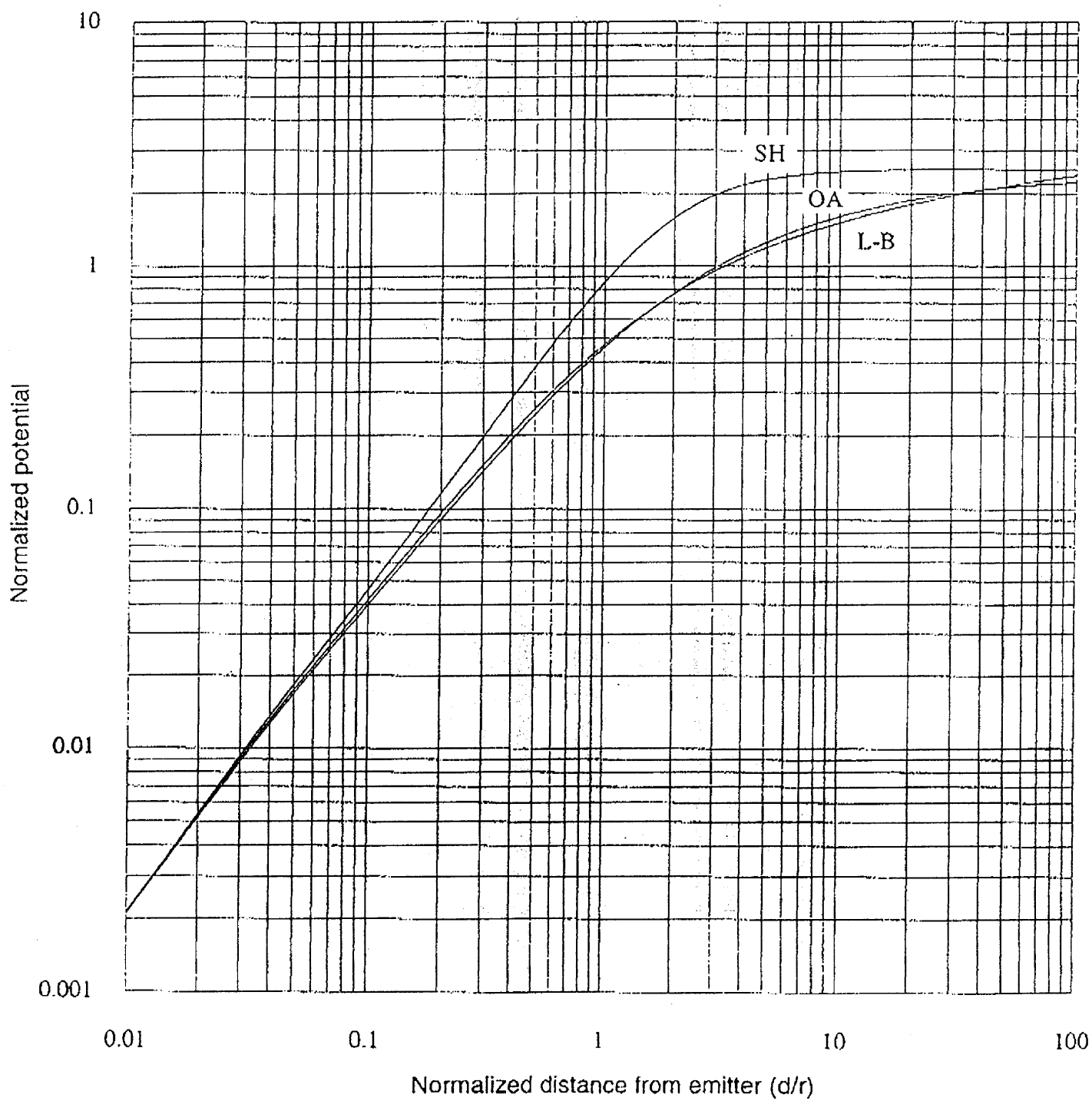


Fig. 2

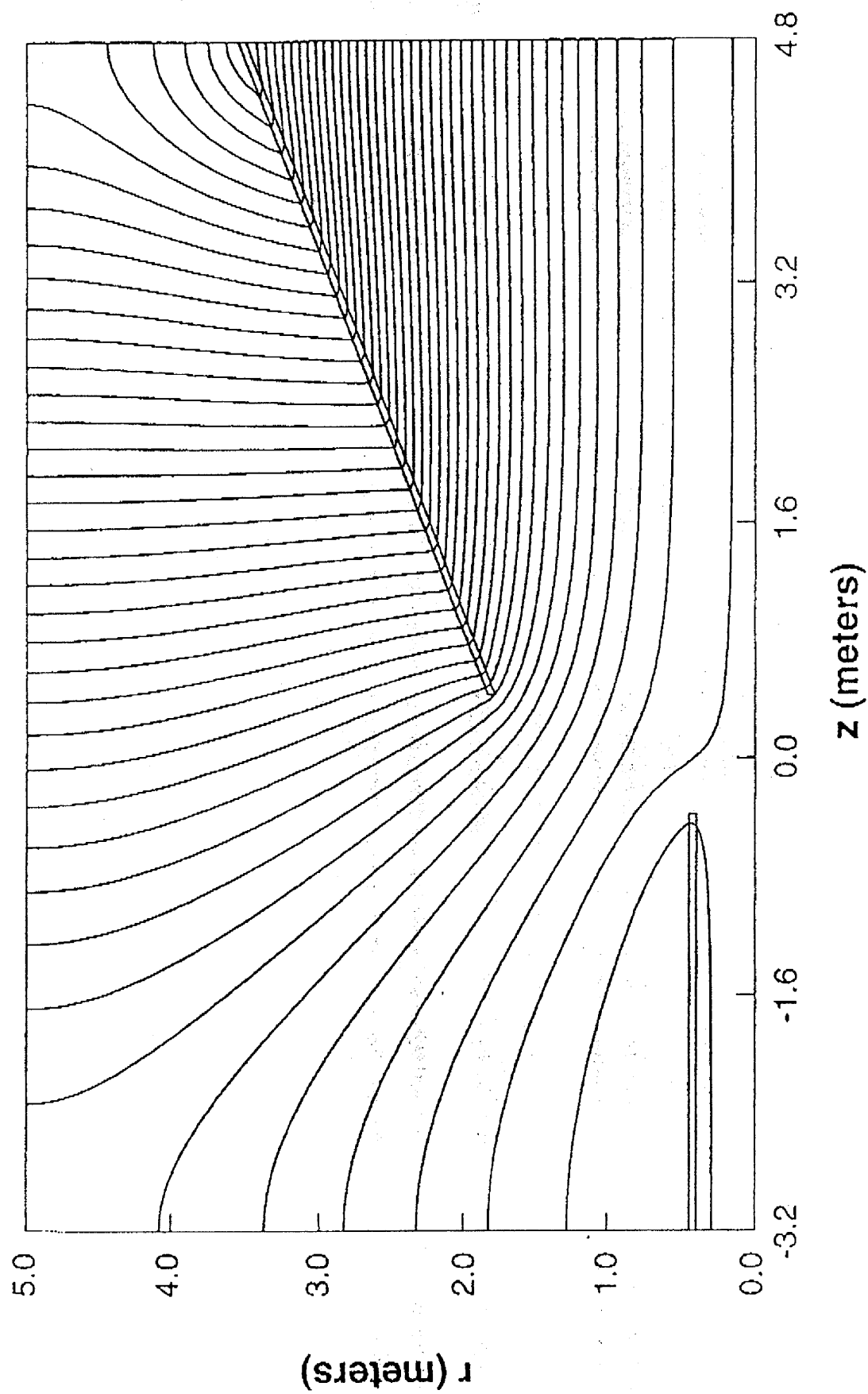


Fig. 3

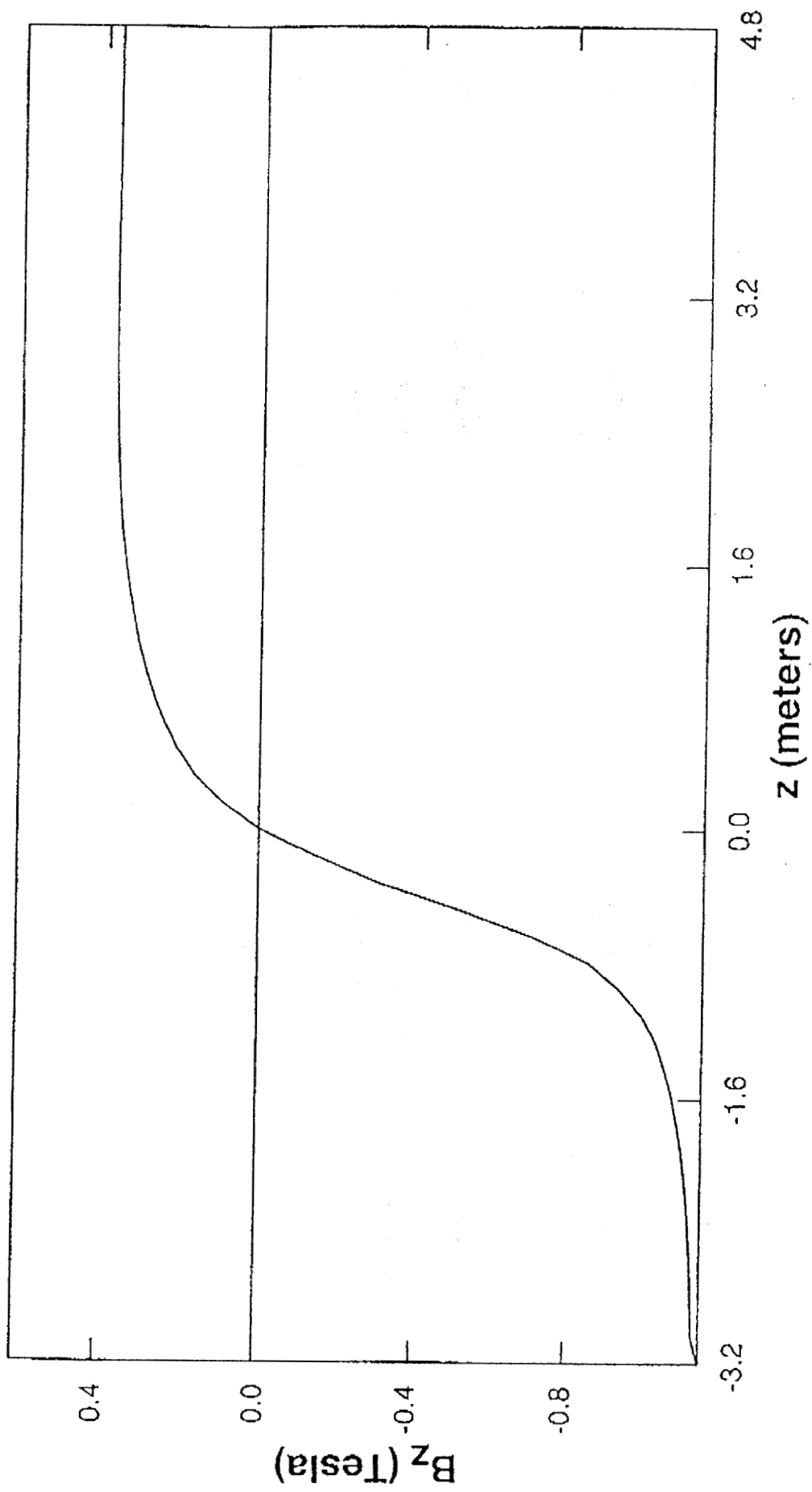


Fig. 4

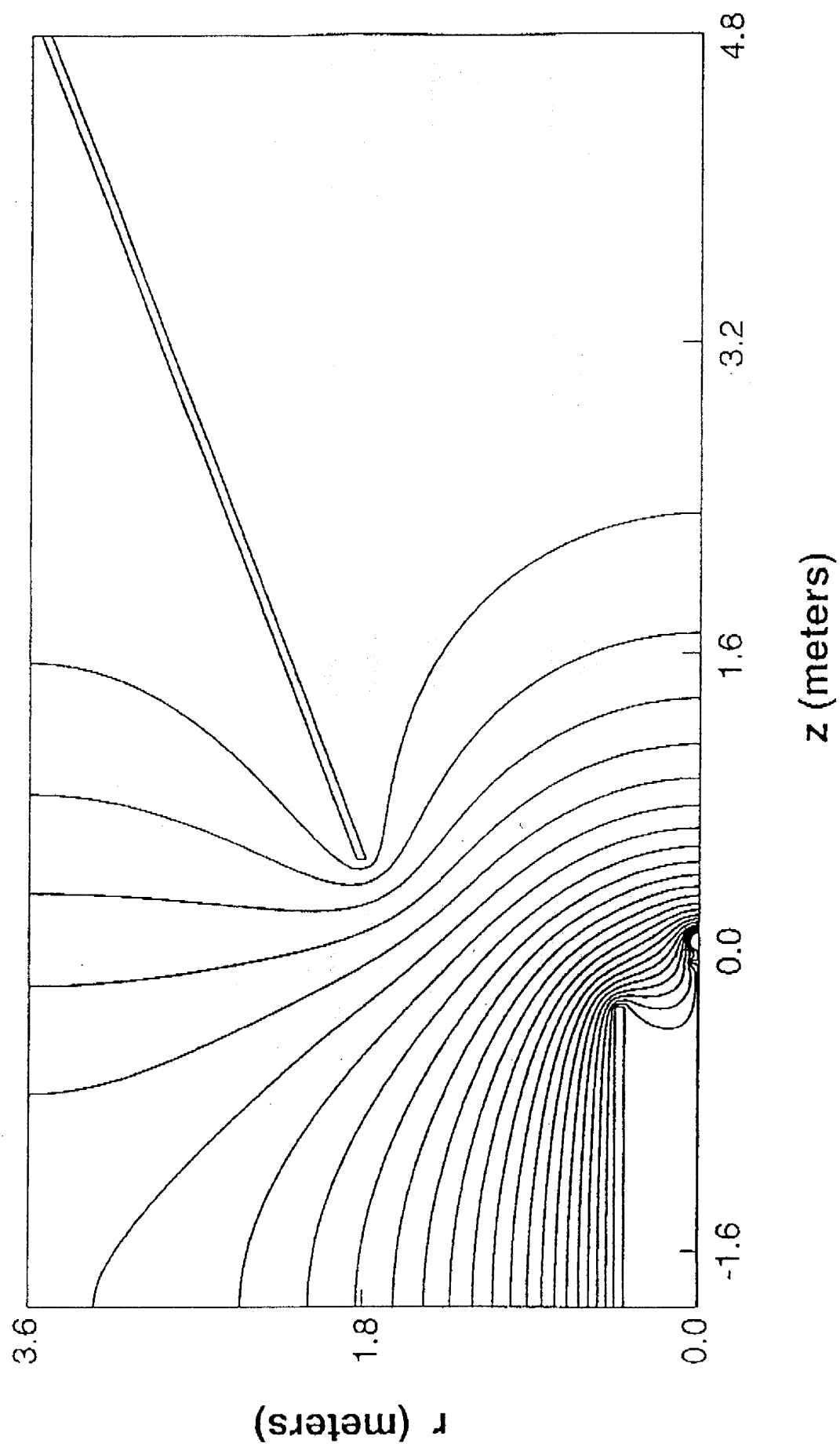


Fig. 5



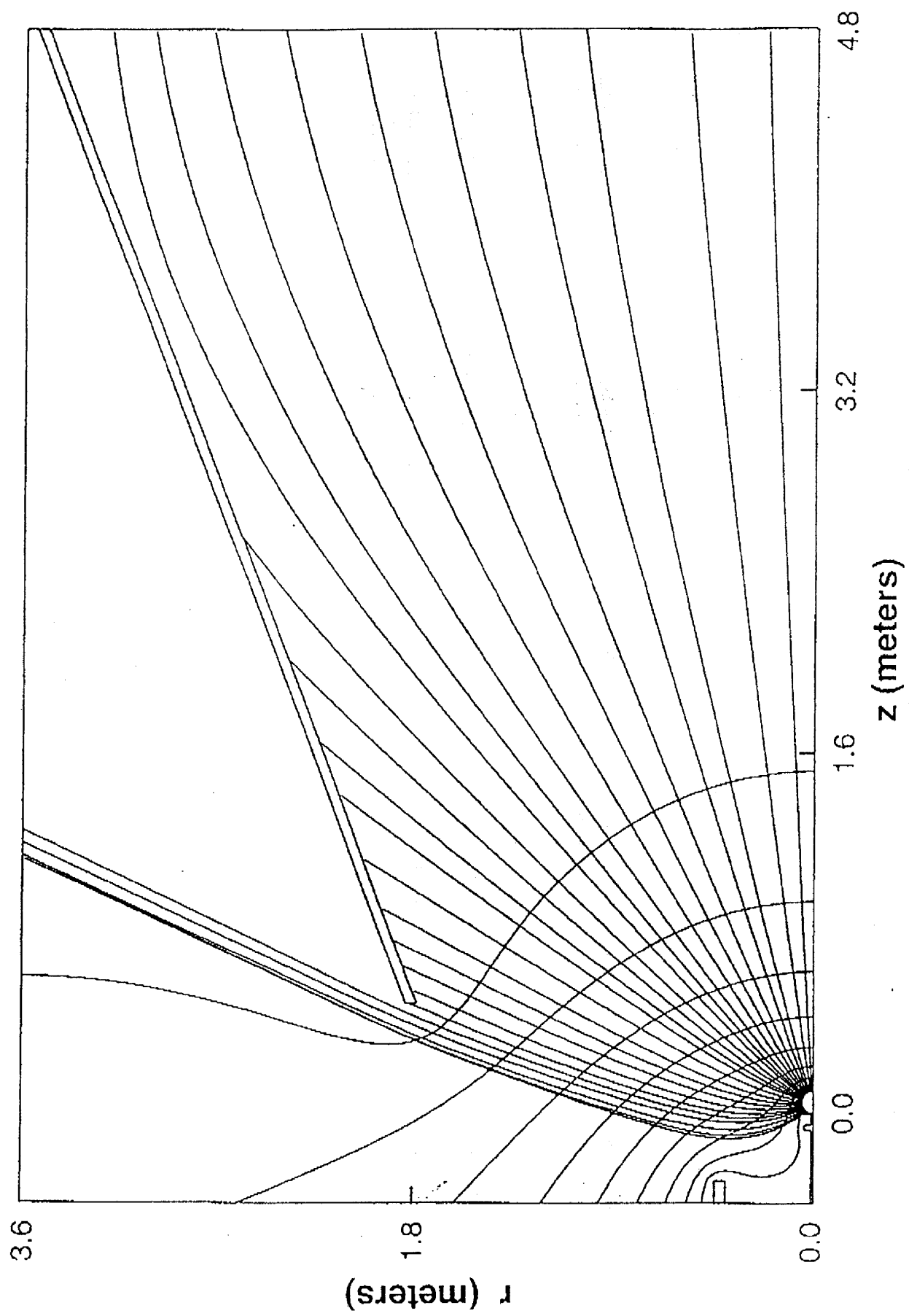


Fig. 6